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Department of Agricultural, Resource, and Managerial Economics
Cornell University, Ithaca, New York 14853-7801 USA

Climate Policy And Petroleum Depletion

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Neha Khanna is a Ph.D. candidate in Resource and Environmental Economics. She is currently on leave from the Tata Energy Research Institute, New Delhi, India.

Duane Chapman is Professor of Resource and Environmental Economics.

Abstract

This paper extends the Nordhaus DICE model to include the demands for coal, oil, and natural gas. These demands depend on own price, prices of substitute fuels, per capita income, and population. An augmented Hotelling model captures the effect of depleting oil resources. A methodological advantage of including price, income, and population sensitive energy demand functions is that it allows substitution possibilities in the 'production' of emissions. Furthermore, it allows the analysis of energy tax regimes in an environment of growing world population and income, non-decreasing energy and carbon intensity, and declining petroleum availability.

Keywords

backstop

climate change

control rate

emissions

energy intensity

energy tax

finite resource

fossil fuel

fuel substitution

optimal growth

prices

resource depletion

Journal of Economic Literature classification number: **Q25** (Water, Air) or **Q43** (Energy and the Macroeconomy)

Our future lies not in the stars, but in our models.

(William Nordhaus, 1994, p. 6)

I. Introduction

The Dynamic Integrated Climate Economy (DICE) model developed by William Nordhaus represents a new genre of economic analysis in the context of climate change. It has been widely published and discussed in the *Economic Journal* and elsewhere. (National Academy of Sciences 1983, Nordhaus 1991, 1992, 1994). In subsequent work, Nordhaus and Zili Yang (1996) expanded this approach to encompass several world regions which may work cooperatively, or each may work in pursuit of maximum benefit for itself. These models combine the standard tools of optimal economic growth with climate modeling. The interaction between these two facets is established via greenhouse gas (GHG) emissions, ocean storage, and climate induced damage that links temperature rise to loss in world output.

The concatenation between optimal economic growth and climate modeling forms the starting point of the current analysis. In this paper, we extend the DICE model by elaborating the relationship of economic growth to petroleum resource depletion and the emissions of GHGs. Carbon emissions depend directly on the levels of coal, natural gas, oil and synfuel consumption. There are finite oil resources that, along with the cost of the backstop, influence the optimal trajectory of oil production. The resulting oil price trajectory affects the demand for the other fuels, and thence, the level of global carbon emissions. As may be anticipated under these plausible conditions, projected climate change can be somewhat greater than otherwise expected.

II. Greenhouse gas emissions and the existence of decarbonization

In the DICE model, Nordhaus projects uncontrolled GHG emissions as proportional to world economic output.[1] The evolution of technology brings two additional forces into play. First, total factor productivity, $A(t)$, increases, so that the production isoquant shifts outward over time. This implies that the same physical quantities of capital, $K(t)$, and labour, $L(t)$, produce an increasing output, $Q(t)$, over time. See equations (1)-(4).

Second, the emissions to output ratio, $\sigma(t)$, decreases monotonically. That is, the ray defining the relation between emissions and output rotates towards the output axis with time. Nordhaus assumes this decline in $\sigma(t)$ on the grounds that it is consistent with historical data and with the results of some energy models. At the same time, he notes that there is a great deal of uncertainty and speculation here, and acknowledges that there is no correct assumption regarding the future trend in the CO_2-GNP ratio. According to his perspective, in the long term this ratio could fall by as much as 1.5% per year or by as little as 0.5% per year (Nordhaus 1994, pp. 66-70).

Furthermore, for both parameters $A(t)$ and $\sigma(t)$, the rate of change declines by a numerically identical amount. These relationships are presented in equations (5)-(9). The variables $g_A(t)$ and $g_\sigma(t)$ denote the rate of change in total factor productivity and carbon intensity, respectively; $E(t)$ represents uncontrolled emissions. All other variables are as defined in the text above. The initial, i.e., 1965, values for all variables are determined from historically observed data.

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[1] Only carbon dioxide (CO_2) and chloroflorocarbons (CFCs) emissions are proportional to output. All other GHGs are determined outside the model and are independent of the level of gross world product.

$$E(t) = \sigma(t) Q(t) \tag{1}$$

$$Q(t) = A(t) K(t)^{\alpha} L(t)^{1-\alpha} \tag{2}$$

$$\sigma(t) = \sigma(1965) e^{g_{\sigma}(t)} \tag{3}$$

$$A(t) = A(1965) e^{g_{A}(t)} \tag{4}$$

$$g_{A}(t) = g_{A}(1965) \eta(\delta_{A}, t) \tag{5}$$

$$g_{\sigma}(t) = g_{\sigma}(1965) \eta(\delta_{A}, t) \tag{6}$$

$$\eta(\delta_{A}, t) = \frac{1 - e^{-\delta_{A} t}}{\delta_{A}} \tag{7}$$

$$\begin{gathered} A(1965) = 0.00963 \\ \sigma(1965) = 0.519 \end{gathered} \tag{8}$$

$$\begin{gathered} g_{\sigma}(1965) = -1.25\% \textit{ per year} \\ g_{A}(1965) = 1.41\% \textit{ per year} \\ \delta_{A} = 1.1\% \textit{ per year} \end{gathered} \tag{9}$$

Combining, we get the following expression for emissions:

$$E(t) = \sigma(1965) A(1965) e^{[\eta(\delta_{A}, t) \{g_{A}(1965) + g_{\sigma}(1965)\}]} K(t)^{\alpha} L(t)^{1-\alpha} \tag{10}$$

The key factors determining the total level of uncontrolled emissions in DICE are, thus, the level of world output and autonomous technological change. The emissions trajectory rises slowly during the entire horizon. The eventual stabilization of emissions is due, in part, to the stabilization in world population and in world economic product. This decline in emissions growth is reinforced by the decline in the growth rate of total factor productivity.

While these factors are important, they are not the only determinants of the emissions profile of an economy. Total emissions depend not only on the amount of output produced, but also on how it is produced. In other words, the fuel mix and factors affecting it: energy prices, per capita income, resource availability, and substitutability, for example, are equally significant factors. At the same time, the carbon intensity of the global economy depends on the relative future growth of presently developing and developed economies. The emissions to output ratio can decline only if, *ceteris paribus*, the observed decline in the carbon intensity of the developed countries more than outweighs the possible increase in the carbon intensity of developing countries, or if both decline. Exactly what will happen is not certain, *a priori*. This is apparent from table 1 which shows the global carbon intensity between 1929 and 1989. While it is true that the carbon-GNP ratio has declined during this entire period, it is instructive to consider two smaller time periods separately. Between 1929 and 1960, the carbon intensity declined sharply. However, the period from 1960 experienced a slight increase, indicating the growing importance of developing countries in the global energy-economy.

Table 1: Global Carbon Intensity, 1929-1989

Year	Tons of C / 1000 1989 US $
1929	0.409
1938	0.366
1950	0.343
1960	0.219
1970	0.219
1980	0.241
1989	0.232

Source: Nordhaus (1994, p. 67)

Note: "Ton" refers to the metric ton and not the U.S. ton.

This trend in carbon intensity is reinforced by an underlying trend in the patterns of energy consumption of high income and other countries. Figure 1 shows energy use per unit of economic output from 1971 to 1992 for 101 countries grouped as high income countries and the rest of the world (ROW) or other countries.[2] While there is a slight upward trend in

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[2] GDP data for this analysis were obtained from the Penn World Tables (version 5.6). Details of this data base are available in Summers and Heston (1991). Energy consumption data were obtained from World Bank (1995). Countries were categorized according to the World Bank's definition of countries by income class

the energy intensity of the countries comprising ROW during this period, energy intensity for the entire sample declined by almost 18%, closely following the strong trend for high income countries. This is because high income countries dominated world energy consumption and output in the past: in 1971 they accounted for 80.4 % of total commercial energy consumption, and 67.7 % of the world's economic product. However, this highly skewed pattern of consumption and output is being slowly eroded with the ROW's share rising steadily (see figure 2).[3] If this trend continues, and we believe it will, then the future global trend in energy intensity is likely to be dominated by the consumption patterns of the ROW countries. This, in turn, is likely to offset the historic decline in global energy intensity.[4] This is contrary to the standard assumptions of many prominent macroeconomic energy and climate change models (see Peck and Teisberg 1992 and 1995, Nordhaus 1994, Nordhaus and Yang 1996, and Manne *et al.* 1995).

Manne and Richels (1992, pp. 32-34) review the literature on this issue, and conclude that there is no econometric evidence of autonomous energy efficiency improvements (AEEI) in post 1947 USA. They claim that the reason for the common assumption of positive AEEI is possibly the optimistic outlook of energy technologists. In their own modeling, they followed the existing practice and hypothesize a positive global AEEI. The AEEI-declining carbon intensity is a highly significant, unresolved issue in climate change policy analysis.

(World Bank, 1994). Countries included in our sample are listed in appendix A.

[3] In both figures 1 and 2, "world" refers to the aggregate for the 101 countries in the sample.

[4] If the existing growth rates for each group of countries were to continue, the global energy intensity curve is necessarily convex, declining now but rising at some future date. Of course, the trade in goods with differing embodied energy is a factor to consider in this analysis.

We have developed a framework to address the issues raised here. Our framework is based on the Nordhaus (1994) model, a brief summary of which is provided in appendix B.

III. Dynamic Integrated Climate Assessment for a Fossil Economy

In the Khanna-Chapman analysis (KCA) there are four carbon based fuels - coal, oil, natural gas, and a coal-based synthetic fuel that acts as the backstop. We assume that the oil market is the driving force of the energy economy. Oil production is determined via an augmented Hotelling-type optimization framework for a market with shifting demand (Chapman 1993). Producers face a rising linear demand curve that shifts outward over time in response to a growing world population and rising per capita incomes. At the same time, extraction costs increase steadily, as specified exogenously. In addition, the backstop cost sets an upper bound on the price of oil. Producers maximize the net present value of profits taking account of these countervailing forces, and also finite remaining resources. The optimal production trajectory is such that remaining oil resources are exhausted when the rising oil price passes the cost of the backstop. (This trajectory is derived analytically in appendix C.)

The per capita demands for coal and for natural gas are determined by per capita income, own prices, and prices of all other fuels through linear homogenous Cobb-Douglas functions. Oil is replaced by a liquid fuel backstop, a synthetic fuel in our case, whose demand is also determined via a similar function in prices and income. Energy prices are assumed to grow steadily.

Finally, carbon emissions are calculated from the aggregate consumption/production of fossil fuels through carbon emission coefficients that translate energy units to tons of carbon.

While the extension of the DICE model represented by the KCA is simple, it incorporates some significant conceptual details. Here we allow for explicit substitution in the "production" of emissions. This substitutability is captured by the cross-price elasticities, and is reflected in the changing fuel shares in total emissions production. In addition, by allowing interfuel substitution, KCA endogenizes the change in energy and carbon intensity that occurs in response to changes in relative prices. Lastly, we do not impose exogenous improvements in future carbon and energy intensity. This is in concert with the discussion, and the data presented in table 1, and in figures 1 and 2. This has important implications since autonomous reductions in carbon and energy intensity could camouflage a significant part of the costs of reducing GHG emissions. The analysis by Chapman *et al.* (1995, pp. 6-7) shows that a stable carbon intensity leads to much higher temperature increases relative to those obtained by Nordhaus. Consequently, with the other parameters remaining unchanged, the optimal control rate rises to approximately 35% per year by 2115 instead of the 14-15% per year in the Nordhaus optimal case.

IV. Parameter values

The only parameters values that differ between KCA and DICE are those for the energy sector. These are summarized in appendix D. All other parameters are assigned the same values to maintain consistency. A few comments:

Fossil fuel prices

Since the early to mid 1980s, the real prices of coal and natural gas have been declining steadily. Prior to that period, they rose sharply as shown in table 2, overleaf. For our analysis, we assume that the real prices for coal and natural gas grow at 0.1% per year starting from the 1995 values. This is roughly consistent with the data from the past three decades for USA. The same growth rate is assumed for the price of the synthetic fuel.

Table 2: Coal and natural gas prices (USA, 1989 dollars)

Year	Coal ($/ton)[a]	Natural gas ($/1000 cf)[b]
1965	21.82	2.27
1975	38.88	2.31
1980	43.52	4.33
1985	39.69	5.40
1990	24.77	3.72
1995	22.56	3.14
Growth rate (% pa):[c]		
1965-1980	+ 4.71	+ 4.40
1980-1995	- 4.29	- 2.12
1965-1995	+ 0.11	+ 1.09

a: refers to the delivered price to utilities

b: refers to the volume weighted price for all consuming sectors

c: authors' calculations based on data presented

Sources: For coal, data are from EIA (1994). For natural gas, price and consumption data are from AGA (1981) and EIA (1996). See appendix D also.

Price and income elasticities

There is no consensus in the literature on the income, own-, and cross-price elasticities of demand for coal and natural gas.[5] Following Drennen (1993, pp. 78-79), we set the income elasticity at 1 and the own-price elasticity at 0.5. The cross-price elasticities are half the own-price elasticity. Since we assume that oil drives the energy economy, the prices of the other fuels do not affect the demand for oil. However, the price of oil has a positive influence on the demand for coal and natural gas. Also, note that as long as oil is being produced, the synfuel does not affect the demand for the other fuels. It is only when oil resources are exhausted that synfuel production begins. Then, its slowly rising price exerts an upward pressure on the demand for coal and natural gas through the cross-substitution effect.[6]

Remaining crude oil resources

Remaining resources refers to the total conventional crude oil available for recovery. It is the sum of undiscovered resources and identified reserves (Chapman 1993, p. 334). Using the ninety fifth percentile point on the frequency distribution for original resources developed by the U.S. Geological Survey, Chapman estimates that the 1990 remaining crude oil resources were 2100 billion barrels. A similar estimate has been used by Manne and Richels (1992: see pp. 38-39 for discussion). To this figure, we added the cumulative production from 1965 to 1990 to obtain an estimate of approximately 2500 billion barrels of

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[5] See Drennen (1993) for a good survey of energy demand elasticities at the global and regional levels.

[6] An alternative specification would blend declining petroleum use with growing synfuel use. However, this would not significantly affect the results considered here.

remaining crude oil resources in 1965.[7] According to Manne and Richels, the ninety fifth percentile constitutes a practical upper bound on undiscovered resources. By using this value we allow for the possibility that technology improvements and future price increases will lead to larger quantities of economically recoverable oil.

Cost of oil extraction

The model is calibrated such that starting from 1965, the average cost of extraction to producers rises to 10 $/bl in 1990 (Chapman 1993) and continues to grow at the same rate thereafter, i.e., 1.61% per year.[8]

V. DICE and KCA: a comparison of results

The Khanna-Chapman model is operated under two scenarios: the base case with no CO_2 control, and the case where the control rate for CO_2 emissions is optimized (the "optimal case"). Following Nordhaus, we discuss results for the first 150 years of the horizon only. The source of any difference in the results of the two models is the energy submodel. Hence, we begin with a discussion of these results first.

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[7] Data for crude production from 1965 to 1990 were obtained from Chapman (undated).

[8] Note that the difference between the market price of crude oil and the cost of extraction is the economic rent on crude oil production.

Per capita energy consumption

Oil production increases monotonically till resources are exhausted.[9] Unlike the original Hotelling model, in the presence of an upwardly shifting demand for oil, production here must be increased in order to equalize the discounted value of profits in every period. This trajectory also maximizes social welfare (Chapman 1993). Under the base case, oil resources are exhausted in 2025, with the peak production at 61.9 billion barrels per year.

As oil is exhausted, production of the synfuel begins. Starting from an initial value that takes up the slack created by the exhaustion of oil resources, the per capita demand for the synfuel rises slowly. The per capita demands for coal and natural gas also rise from the initial (1965) values. For each of these fuels, the positive income and cross-substitution effects on demand more than outweigh the negative own price effect. In part, this is due to the elasticity values assumed, and in part due to the relative growth rates of energy prices and per capita income. Figure 3 shows the per capita fuel consumption for the base case.

Oil price

As expected, the market equilibrium price of crude oil rises continuously till it reaches the upper bound set by the cost of the backstop (55 $/bl). Prices for all fuels are shown in figure 4.

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[9] In the absence of a backstop, the augmented Hotelling framework results in near term growth in market equilibrium quantities before the eventual decline to depletion. This contrasts to the simple Hotelling framework in which the equilibrium declines monotonically.

Carbon emissions

Figure 5 compares the carbon emissions trajectories obtained under the DICE and KCA base cases. The latter model yields much higher emissions levels. By 2105 the KCA value is more than two and a half times the value generated by DICE. Two factors explain this divergence. First, due to the exogenous decarbonization imposed by Nordhaus, emissions are a continuously declining ratio to output. Starting from an initial value of 0.519 in 1965, this fraction falls to 0.229 by 2105.[10] In contrast, there is no autonomous energy efficiency imposed in KCA. Second, the synthetic fuel in KCA releases a higher amount of carbon per unit of energy than oil or coal (see appendix D). Thus, emissions get an added impetus when synfuel production begins in 2035.[11]

Carbon and energy intensity

As mentioned above, the exogenous decarbonization implies that the carbon intensity of the DICE economy declines steadily. In the KCA, this is not the case. Initially, the carbon intensity rises slowly. When synfuel production comes on-line to replace crude oil, the CO_2-GNP ratio rises sharply due to the relatively higher carbon intensity of this fuel. Thereafter, the ratio remains more or less stable. Energy intensity rises from 17 thousand BTU/$ in 1965 before stabilizing at about 23-24 thousand BTU/$.

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[10] The ratio of CO_2-GNP continues to decline further, till it eventually stabilizes at about 0.19.

[11] A qualification about the comparability of the results from the two models: in the Nordhaus (1994) model "emissions" refer to a combination of CO_2 emissions and CO_2-equivalent CFC emissions. Our model considers only the former, as does the latest work by Nordhaus and Yang (1996).

This is an intuitively appealing result. For the next few decades, while a large proportion of the world's population in developing countries strives to meet its basic energy needs, the energy and carbon intensity of the global economy is likely to increase. Once these nations have acquired some minimum level of per capita income and energy consumption, and as energy prices rise world-wide, there will be an increased effort to reduce per unit energy consumption, resulting in the subsequent stabilization in energy and carbon intensities. This is shown in figure 6.

Under the optimal case, while the qualitative trends remain unchanged the absolute levels fall somewhat when optimal controls on carbon emissions are brought into effect. Both carbon and energy intensity decline slightly before stabilizing.

Temperature rise

Both DICE and KCA measure climate change in terms of the rise in atmospheric temperature above the 1865 level. Due to the higher level of emissions resulting here, we observe a greater temperature rise. In 2105, the results of the two models differ by more than 1°C. Note that because of the lags in the system, the difference in temperature becomes more evident with time. Hence, in figure 7 we display the rise in temperature over the entire 400 year horizon. From the 22nd century onwards, the KCA values are approximately one and a half times the corresponding DICE values.

Control rate for CO_2 emissions

The optimal control rate for carbon emissions under both models is shown in figure 8. As expected, the control rate under our model is significantly higher than the corresponding value obtained by Nordhaus, reaching approximately 21.5% per decade in 2105 as compared to 14% per decade under DICE. This need for greater control is a result of the higher level of emissions, which arises from the explicit consideration of energy types, petroleum depletion, and a continuation of the observed constancy in carbon intensity. Note that the relationship between the emissions level and the optimal control rate is not linear homogenous. The damage and cost functions posited by Nordhaus are such that a doubling of the emissions level raises the optimal control rate by less than double.

VI. A tax policy simulation

By explicitly incorporating energy prices, the Khanna-Chapman framework facilitates the analysis of alternative energy tax scenarios. The impact of an energy tax on the emissions trajectory depends on the simultaneous interplay of the following forces. First, as the marginal cost of oil extraction increases due to the imposition of an exogenous tax, the optimal production horizon changes, and therefore, the optimal price and quantity trajectories change. The exact paths depend on the interaction between the intertemporally increasing demand for oil, and the rising marginal cost of production. Second, the introduction of synthetic fuels, the most carbon intensive of all the fuels considered, depends on the optimal production horizon for oil. Third, there are substitution possibilities between the various fuels. This means that as the price of a fuel rises there is not only the decline in emissions due to the negative own price effect on demand, but also a partially offsetting increase in the emissions level due to the positive cross-price effect on the demand for substitute fuels.

In this section we simulate the effectiveness of three tax scenarios in lowering the emissions trajectory towards the optimal level.[12] Under the first two scenarios, we impose taxes at differential rates that are ranked according to the relative carbon intensities of the fossil fuels, with the tax rates in the second case being twice as high as in the first case. The third scenario is designed such that the resulting emissions trajectory approximately tracks the optimal emissions trajectory obtained earlier. The exact tax rates used for the analysis are shown in table 4, overleaf.

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[12] Note that this is a simulation and not an optimization exercise. The base case trajectory of per capita income is treated as an exogenous variable for this section of the analysis.

Table 4: Tax rates and levels under alternative scenarios

	Scenario 1 (Low tax)			**Scenario 2** (Medium tax)			**Scenario 3** (Optimal control)		
	Rate (%)	Level of tax		Rate (%)	Level of tax		Rate (%)	Level of tax	
		1995	2105		1995	2105		1995	2105
Oil ($/bl)[a]	20	2.2	12.6	40	4.3	25.1	100	10.8	62.8
Coal ($/ton)	30	6.8	7.6	60	13.5	15.1	200	45.1	50.4
Nat. Gas ($/1000 cf)	10	0.3	0.4	20	0.6	0.7	100	3.1	3.5
Synfuel ($/bl)[b]	40	-	23.6	80	-	47.2	300	-	177

a: The tax is levied on extraction.

b: The tax is levied once synfuel production begins in the decade of 2035.

As evident from figure 9, the first two scenarios have limited success in reducing the emission levels to the optimal trajectory. For this to be achieved, we require extremely high tax rates, an example of which is shown in scenario three, which raise energy prices by as much as four times, as in the case of the synthetic fuel.

VII. Conclusions

This paper extends the seminal work by William Nordhaus on climate change. An explicit treatment of energy-economy interactions which takes account of resource depletion is incorporated. The result is a framework that allows the analysis of the effects of specific energy technology developments, such as changes in the cost and nature of the backstop technology, and also impacts of energy taxation on carbon emissions. The model yields a much higher level of carbon emissions accompanied by a higher optimal control rate, relative to that obtained in the DICE model. The bottom line is the ensuing need for greater, quicker and, consequently, more expensive abatement efforts.[13]

The analysis herewith raises an important question for international climate policy. There is a sizeable body of literature that has persuasively argued that it would be inappropriate for developing countries to pay for GHG emissions reductions.[14] Indeed, the Climate Change Convention recognizes that developed countries must accept historical responsibility for the currently excessive GHG concentrations. In this context, it is unlikely that developing countries will accept the high emissions control rates resulting from analyses

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[13] It is worth noting that some of the trends obtained in this exercise may become intensified if we were to consider also finite natural gas resources. Then, as Manne and Richels point out (1992, pp. 48-49), the sharply rising price of natural gas could erode its competitive edge over coal, specially in electricity generation, reinforcing the pressures for increased coal use.

[14] See, for instance, Shue (1993), Grubb (1995), Khanna and Chapman (1996), and most recently, IPCC (1996), especially chapter 3.

such as the present one. This, in turn, would necessitate the formulation of economic incentives so as to make the GHG reductions ethically and politically palatable.

Furthermore, we find that high levels of energy taxation would be required to reduce the carbon emissions to their optimal level. In the current economic and political setting it seems unrealistic to expect these to be implemented. Yet, any delay in their implementation might warrant even higher taxation in the future.

We have modeled a world in which there is a commercially viable substitute for petroleum use. However, it is possible that there is no suitable backstop technology that will be available to supply liquid fuel on a global basis. In this case, our framework can be appropriately modified. Oil production would continue till resources were exhausted, with the price of oil increasing without an upper bound set by the cost of the backstop. As oil resources approach exhaustion, the demand functions for coal and natural gas would shift in response to the slack in energy availability.[15]

One can only conjecture what will happen when oil becomes relatively scarce. A common approach is to assume that a carbon free backstop, such as hydrogen produced by carbon free electrolysis, or solar and nuclear power, will take its place. See, for instance, Manne and Richels (1992) and Peck and Teisberg (1993).[16] This presumption is particularly important in the global warming context because, in a sense, it describes the "don't worry, be happy" approach: if you wait long enough, the problem will solve itself because the very

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[15] In this case, transportation may shift to more costly electric vehicles, with power produced from coal, nuclear power, or solar energy.

[16] A contrasting view is expressed by Drennen et al. (1996).

source of the problem will begin to disappear. In this analysis, we consider the problem from a different perspective where oil may be replaced by an even more carbon intensive substance, such as a coal or shale based synthetic fuel, for an appreciable length of time. This is accompanied by a continuation of rising energy intensity in developing countries such that the oft posited decline in global energy and carbon intensity from current levels is not realized. In this case, our analysis shows that the greenhouse problem is exacerbated.

This line of thinking might be considered overly pessimistic in the context of other work such as that cited here. The important point is that it is a possibility that should not, nay cannot, be ignored.

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APPENDIX A

Country names and groupings

High income countries

1. Australia
2. Austria
3. Belgium
4. Canada
5. Cyprus
6. Denmark
7. Finland
8. France
9. Germany
10. Hongkong
11. Iceland
12. Ireland
13. Israel
14. Italy
15. Japan
16. Luxembourg
17. Netherlands
18. New Zealand
19. Norway
20. Spain
21. Sweden
22. Switzerland
23. U.K.
24. U.S.A

Other countries

1. Algeria
2. Argentina
3. Bangladesh
4. Benin
5. Bolivia
6. Brazil
7. Burkina Faso
8. Burundi
9. Cameroon
10. Cape Verdi
11. Central African Rep.
12. Chad
13. Chile
14. China
15. Colombia
16. Comoros
17. Congo
18. Costa Rica
19. Dominican Rep.
20. Ecuador
21. Egypt
22. El Salvador
23. Gabon
24. Gambia
25. Ghana
26. Greece
27. Guatemala
28. Guinea
29. Guinea-Bissau
30. Guyana
31. Honduras
32. Hungary
33. India
34. Indonesia
35. Iran
36. Ivory Coast
37. Jamaica
38. Jordan
39. Kenya
40. Korea
41. Madagascar
42. Malawi
43. Malaysia
44. Mali

Other countries (continued)

45. Mauritania
46. Mauritius
47. Mexico
48. Morocco
49. Mozambique
50. Nicaragua
51. Nigeria
52. Pakistan
53. Panama
54. Papua New Guinea
55. Paraguay
56. Peru
57. Philippines
58. Poland
59. Portugal
60. Rwanda
61. South Africa
62. Senegal
63. Seychelles
64. Sierra Leone
65. Sri Lanka
66. Sudan
67. Syria
68. Thailand
69. Togo
70. Trinidad & Tobago
71. Tunisia
72. Turkey
73. Uganda
74. Uruguay
75. Venezuela
76. Zambia
77. Zimbabwe

APPENDIX B

A brief overview of the Nordhaus DICE model and the Khanna-Chapman modification[17]

The DICE model comprises a representative agent, optimal growth model with an intertemporal objective function which maximizes the present value of utility. A unique feature of the model is the linkage of these economic relationships with several significant geophysical relationships that are a stylized presentation of a global circulation model. The decision variables are the rate of investment and the fraction by which GHG emissions are reduced. These variables are analogous to investment in tangible capital in the Ramsey (1928) model: present consumption must be curbed to decrease GHG emissions which would ameliorate climate change which, in turn, would allow higher levels of future consumption.

The world economy produces a composite economic product using a constant returns to scale, Cobb-Douglas production function in capital, labour and technology. Production is associated with the emissions of GHGs. The DICE model assumes that only CO_2 and chloroflorocarbons (CFCs) are controlled. Other GHGs are determined exogenously. The uncontrolled level of emissions in any period is proportional to the level of output. The transformation parameter is assumed to decline over time, according to the growth in total factor productivity.

The accumulation of GHGs in the atmosphere depends not only on the emission levels, but also on the rate at which carbon diffuses into the deep ocean. The ambient

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[17] This section is based on Nordhaus (1994, pp. 7-21). The GAMS program for the model is presented in pp. 191-197. The regional RICE model is defined in the appendix to Nordhaus and Yang (1996).

atmospheric carbon level in any period, therefore, depends on two parameters - the atmospheric retention ratio and the rate of transfer to the deep ocean. These parameters are assumed to be time invariant.

With the accumulation of GHGs comes the rise in global mean surface temperature. The relation between GHG emissions and increased radiative forcing has been derived from empirical studies and climate models. The link between increased radiative forcing and climate change is established by another geophysical relation that incorporates the lags in the warming of the various layers in the climate system, such that a doubling of ambient CO_2 emissions increases radiative forcing by 4.1 watts per meter square.

The economic impact of climate change, represented by the fraction of output lost, is a quadratic function in the increase in atmospheric temperature. The cost of reducing emissions is also assumed to increase with the rise in temperature through an empirically determined relationship. Damage and cost relations come together through an additional shift parameter in the production function.

Finally, the model is designed to maximize the discounted value of the utility of per capita consumption, using a pure rate of time preference of 3% per year. The model has a horizon of 400 years starting from 1965, and operates in time steps of one decade.

In Nordhaus's formulation of the DICE model, emissions in any period are a fraction of gross world output. Over time, as technology evolves this fraction declines and eventually levels off. Our formulation of the model has the methodological advantage of incorporating other factors that directly influence the emissions level. The model takes cognizance of various fossil fuels, each of which result in different levels of CO_2 emissions per unit of energy. The quantity of each fuel consumed in any period depends on both economic forces (relative prices and per capita income) and technology (elasticities of substitution). Furthermore, there are finite resources for some fuels. Thus, the level of CO_2 released depends not only on the level of output produced, but also on the interplay of other factors.

APPENDIX C

Optimal trajectory for crude oil production in a competitive market[18]

Producers maximize the net present value (*NPV*) of competitive profits by choosing the optimal duration of oil production, *T*, and the quantity produced at each time, q_t, given the demand and cost schedules. Following Chapman (1993) this can be represented as:

Maximize *NPV* w.r.t. $[q_t\ ,\ T]$, where

$$NPV = \sum_0^T \frac{[P_t(q_t,\ L_t,\ Y_t) - C(t)]\,q_t(\cdot)}{(1+r)^t} \tag{C1}$$

$$P_t(q_t,\ L_t,\ Y_t) = \beta_2 L_t Y_t^{\gamma} - \beta_1 q_t \tag{C2}$$

$$\sum_0^T q_t \leq S \tag{C3}$$

$$P_t,\ q_t,\ P_t - q_t \geq 0 \tag{C4}$$

where P_t: price of oil at time t

T: optimal duration of production

L_t: population at time t

r: pure rate of time preference

β_1: slope of demand curve

γ: income elasticity

q_t: production of crude oil at time t

C_t: cost of extraction at time t

Y_t: per capita income at time t

S: remaining oil resources

β_2: calibration constant

ϕ: growth rate of extraction cost

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[18] Chapman (1993) also details results for a monopolistic oil market and a sequence of a near-term competitive market followed by a monopolistic market.

The Hamiltonian for this problem is:

$$H = \frac{[P_t(q_t, L_t, Y_t) - C(t)]}{(1 + r)^t} - \lambda_t q_t, \quad \frac{\partial P}{\partial q} \equiv 0 \tag{C5}$$

where λ is the co-state variable, representing the change in the discounted *NPV* due to a small change in the quantity of remaining crude resources. The optimal trajectory can be found by solving the first order conditions and constraints simultaneously. The solution is:

$$q_t = \beta_{3_t} + \frac{(1 + r)^t}{M(r)}(S - \beta_4) \tag{C6}$$

$$\beta_{3_t} = \frac{\beta_2 L_t Y_t^{\gamma} - C(t)}{\beta_1} \tag{C7}$$

$$\beta_4 = \sum_0^T \beta_{3_t} \tag{C8}$$

$$M(r) = \sum_0^T (1 + r)^t \tag{C9}$$

The optimal duration of production, T, is the minimum of T_1 and T_2 :

$$T_1 = T\colon \beta_2 L_t Y_t^{\gamma} = C(t) \tag{C10}$$

$$T_2 = T\colon P_t = k \tag{C11}$$

where k is the exogenously specified cost of the backstop.

In the Khanna-Chapman model, equations (C2) and (C7) through (C11) determine the optimal production and price trajectory for crude oil simultaneously with per capita income and the other variables in the model.

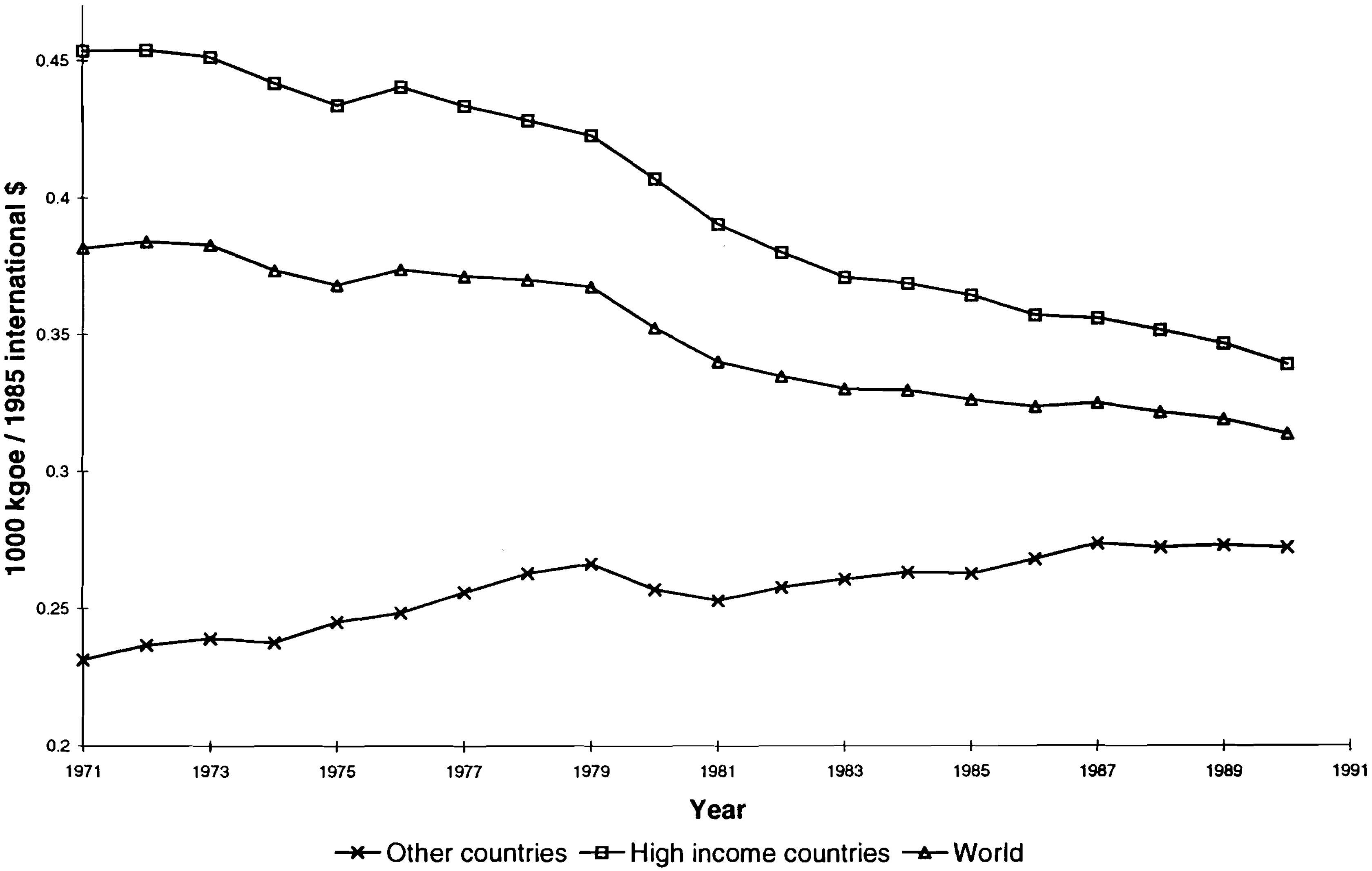
APPENDIX D: Parameter values

Parameter	**Value**	**Data sources**
Energy demand elasticities		
own-price	- 0.5	Drennen (1993)
cross-price	0.25	
income	1	Drennen (1993)
Energy prices: 1965, 1995		
coal (price to utilities, $/bl)	21.82, 22.56	EIA (1994 and 1996, respectively)
natural gas ($/1000 cf)	2.27, 3.14	AGA (1981), and EIA (1996).
Growth rate (% per year)	0.1	
Per capita energy consumption: 1965		Based on energy data from Brown *et al.* (1995), and population data from Nordhaus (1994).
coal (mbtu)	15.58	
natural gas (mbtu)	7.14	
Cost of backstop		
Initial value ($/bl)	55	
Growth rate (% per year)	0.1	
Cost of extraction		Based on Chapman (1993)
1965 value ($/bl)	6.71	see text
Growth rate (% per year)	1.61	
Carbon coefficients (BTC/quad)		Based on Manne and Richels (1992)
coal	0.0254	
oil	0.0210	
natural gas	0.0144	
synfuel	0.0421	

Note: 1. Data are in 1989 $ where applicable. The base year was changed using the implicit GDP deflators obtained from EIA (1994) and BEA (1996)

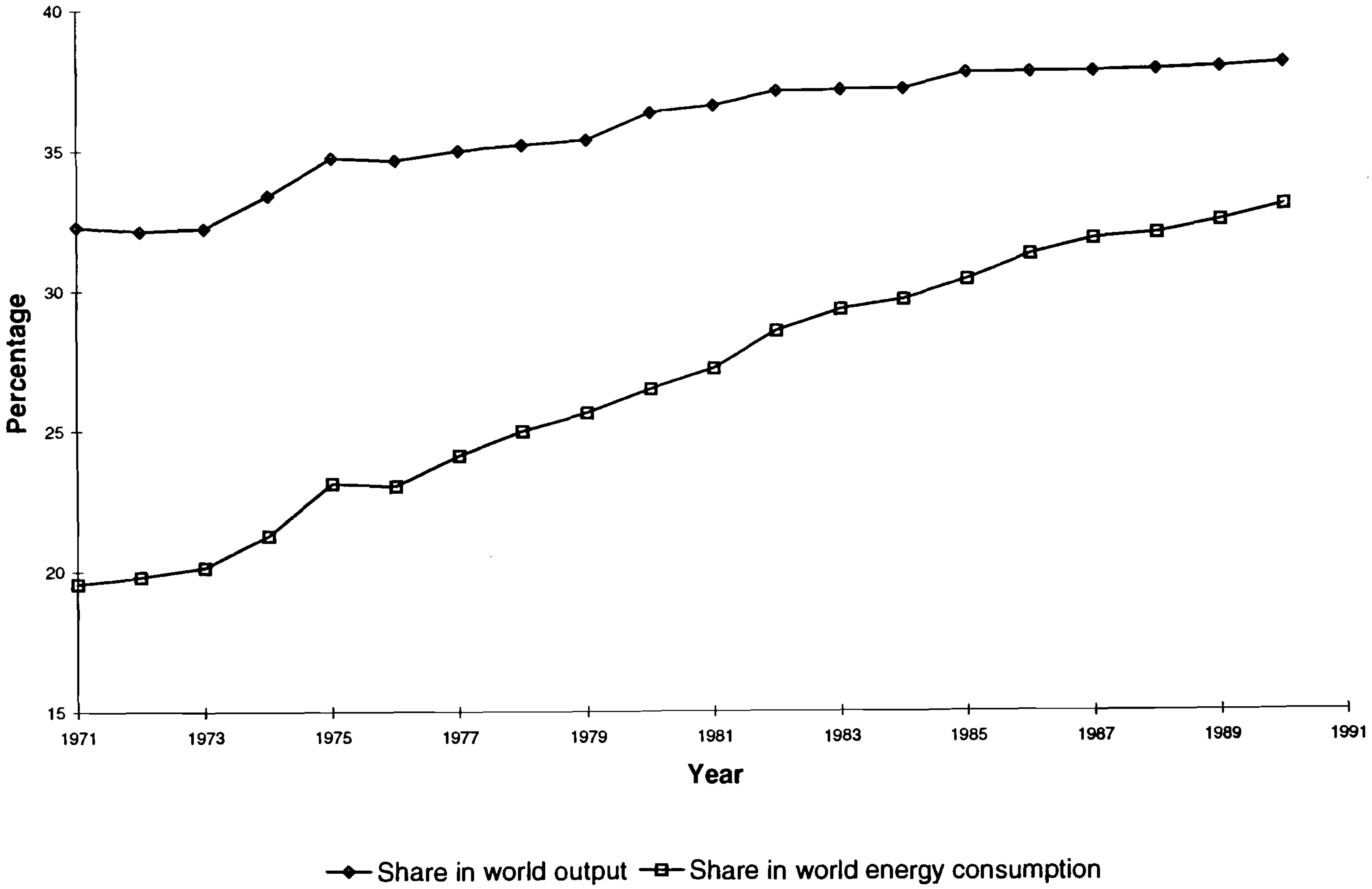
2. Natural gas price is the volume weighted average for all consuming sectors.

Fig. 1: Observed Energy Intensity, 1971-1990



World refers to the sample of 101 countries
International $ refers to a weighted average of international currencies. See Summers and Heston (1991) for details.

Fig. 2: ROW Share in World Output and Energy Consumption, 1971-1990



ROW refers to all countries except high income countries
World refers to the sample of 101 countries

Fig. 3: Per Capita Energy Consumption
(base case)

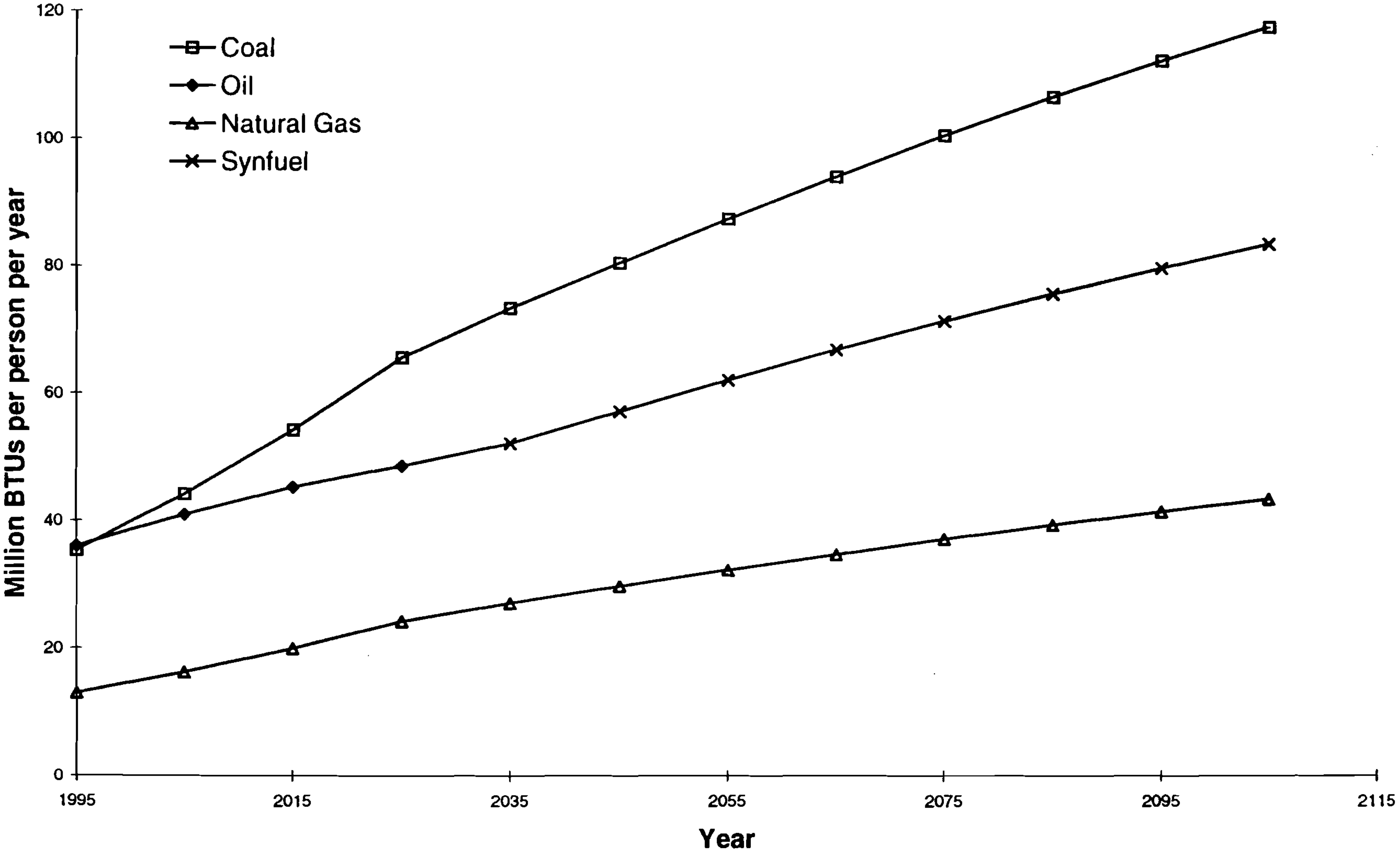


Fig. 4: Energy Prices

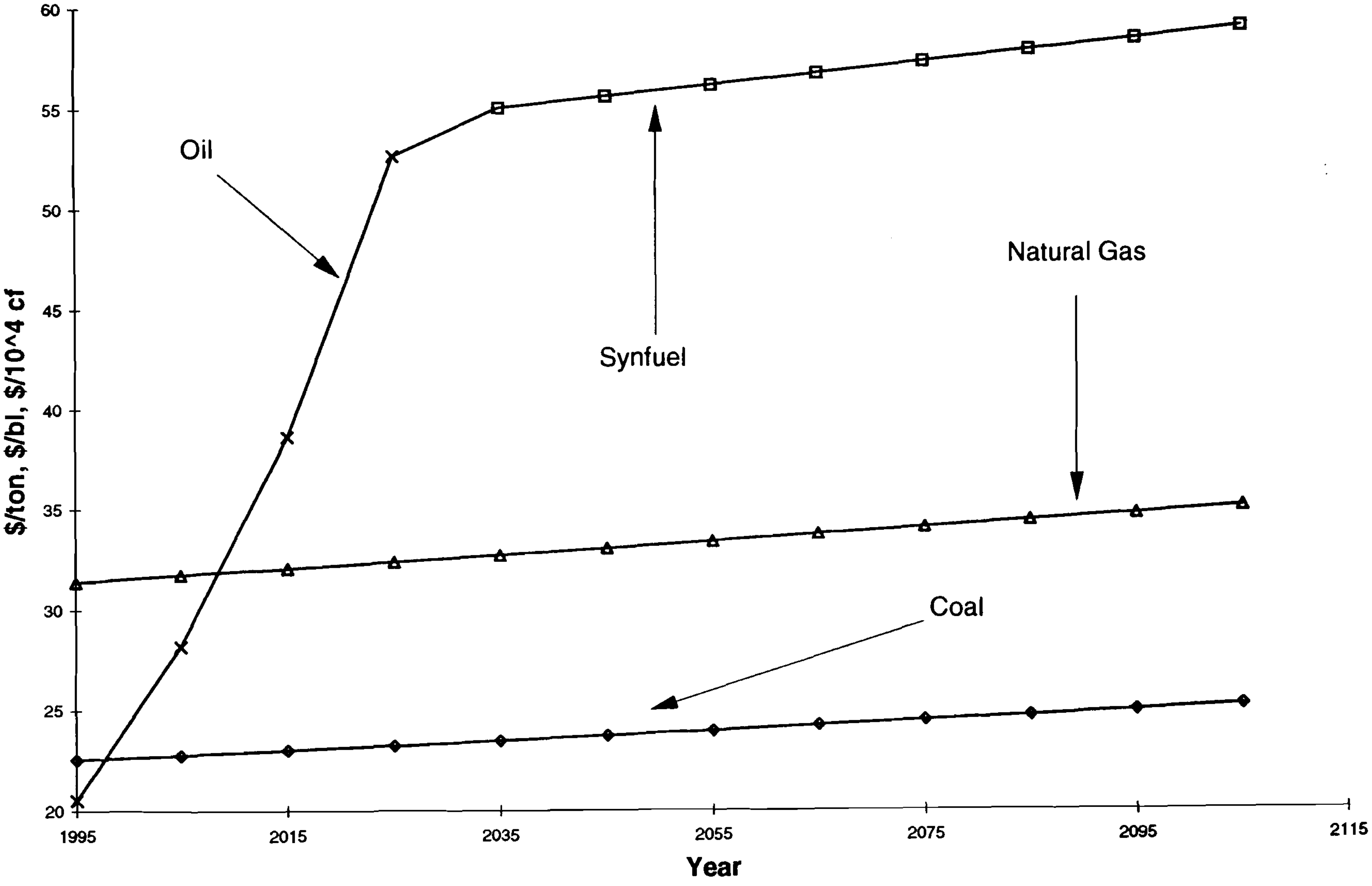


Fig. 5: Carbon Emissions
(base case)

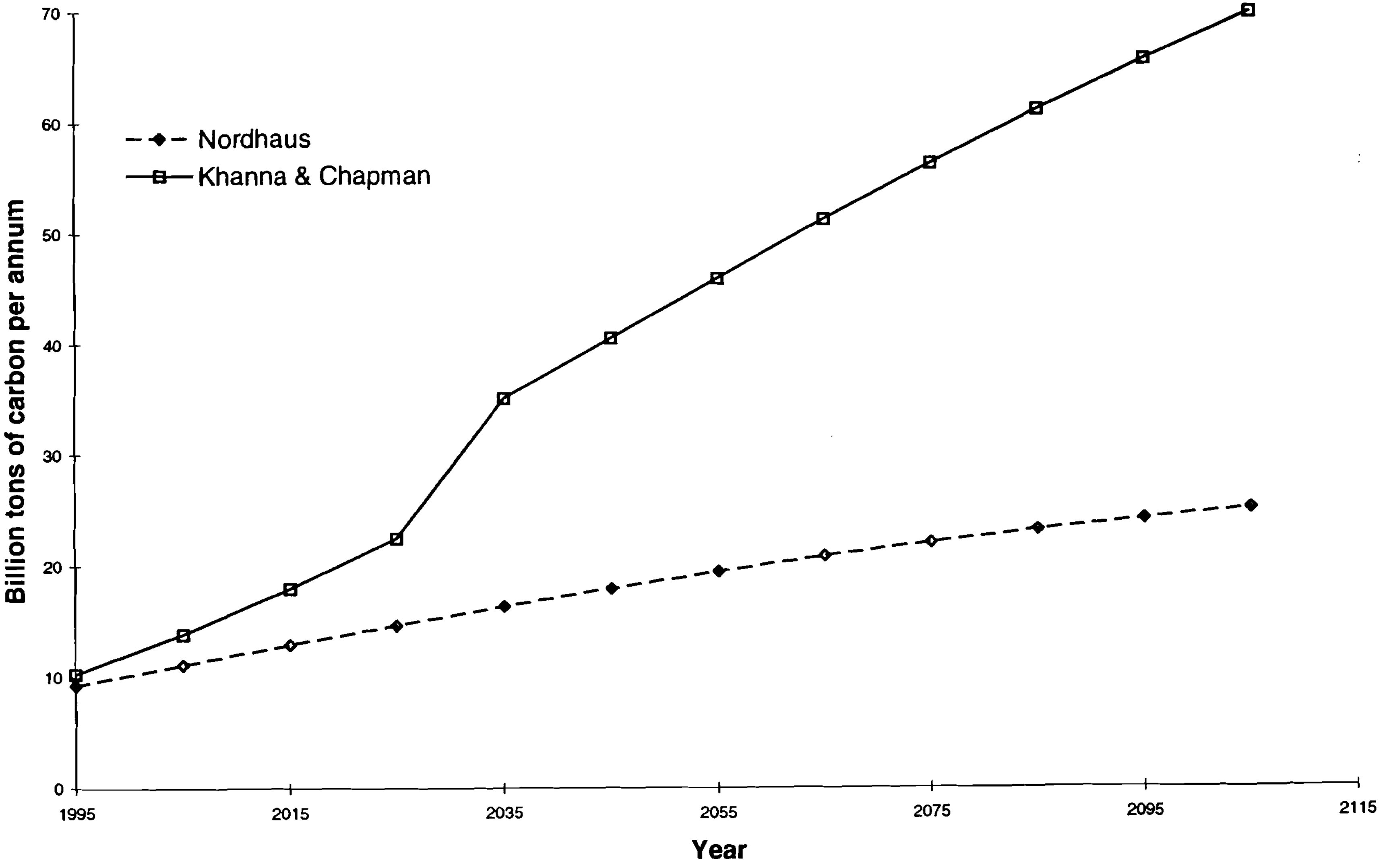


Fig. 6: Projected Energy and Carbon Intensity (base case)

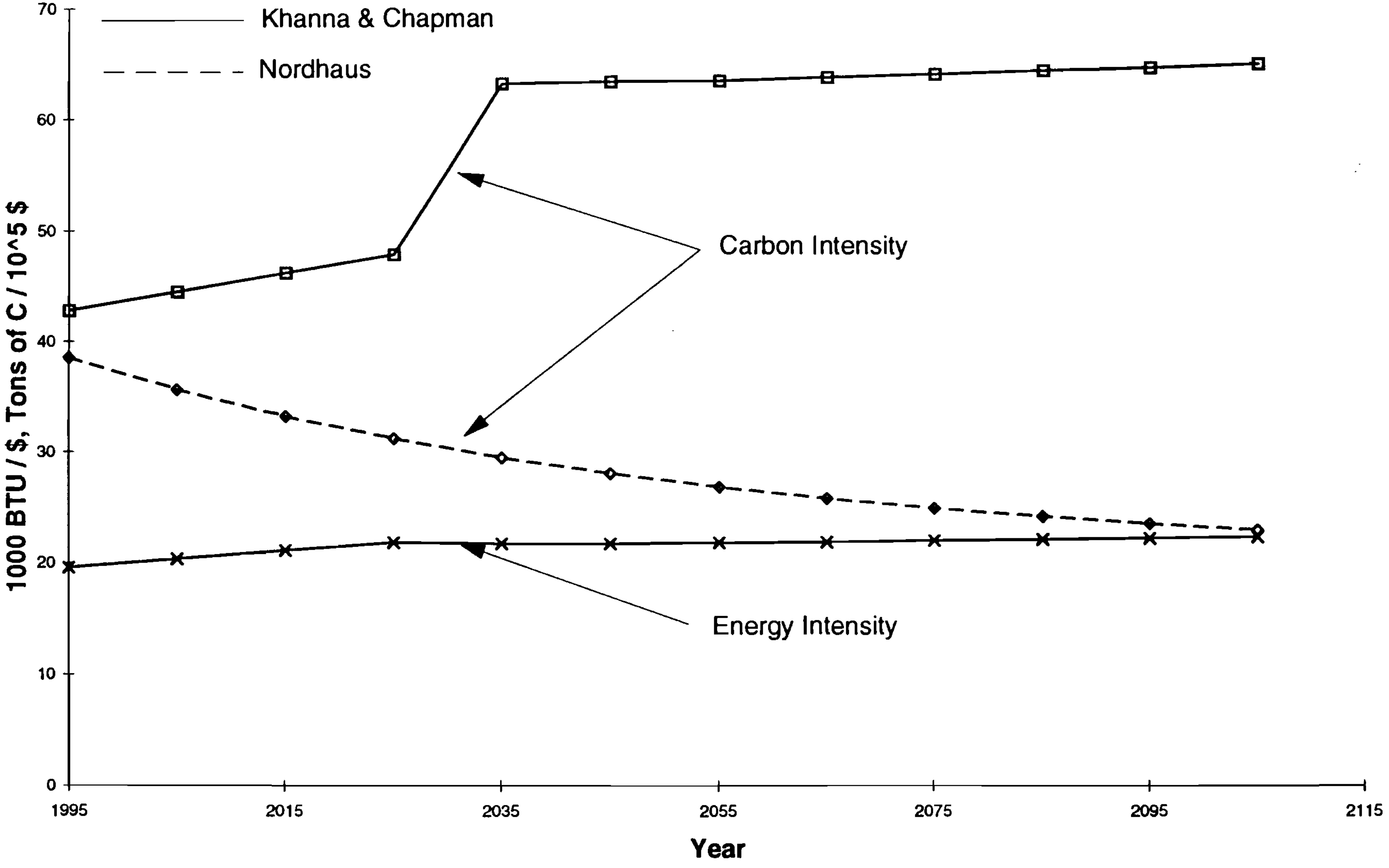


Fig. 7: Rise in Mean Surface Temperature
(base case)

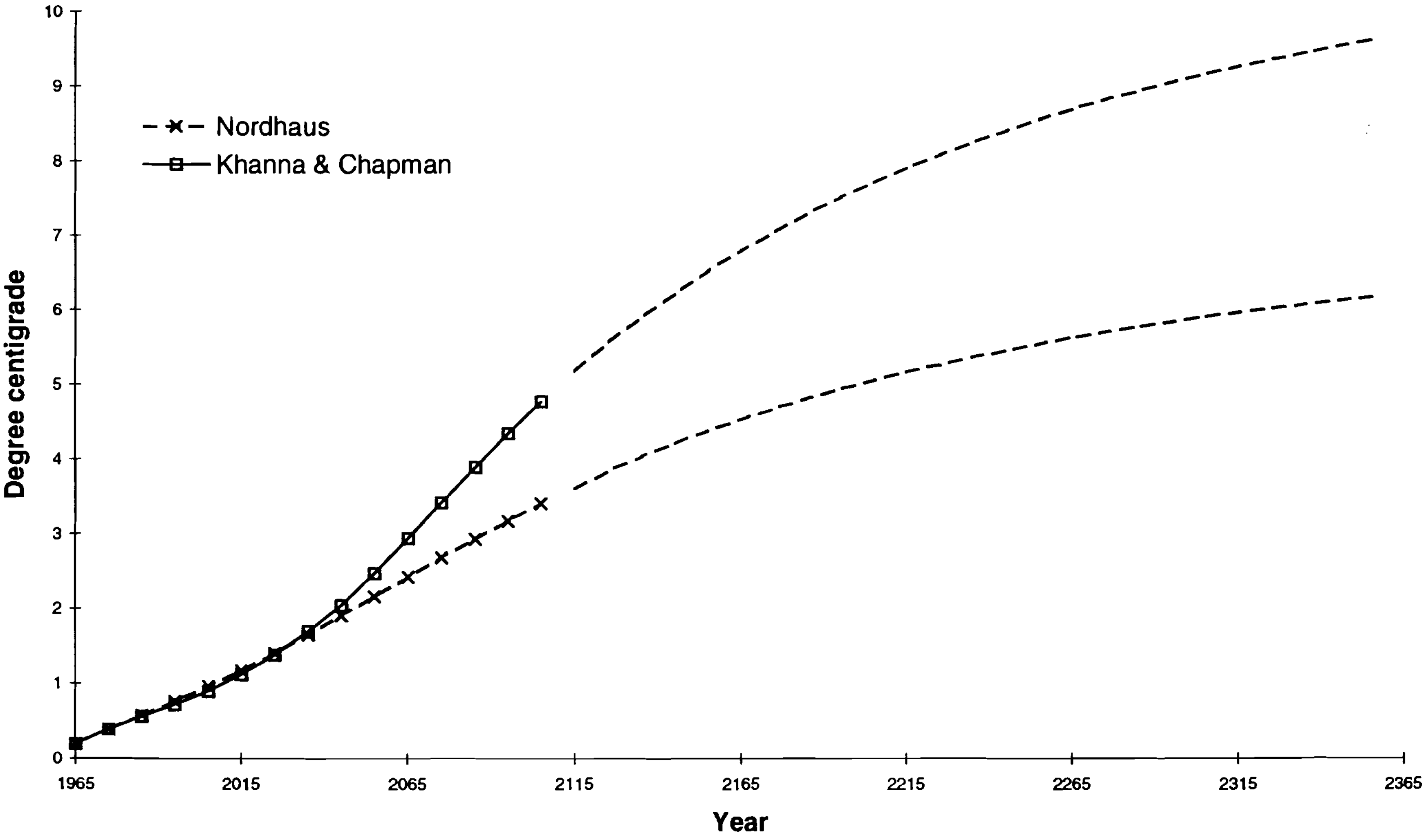


Fig. 8: Optimal Control Rate for Carbon Emissions

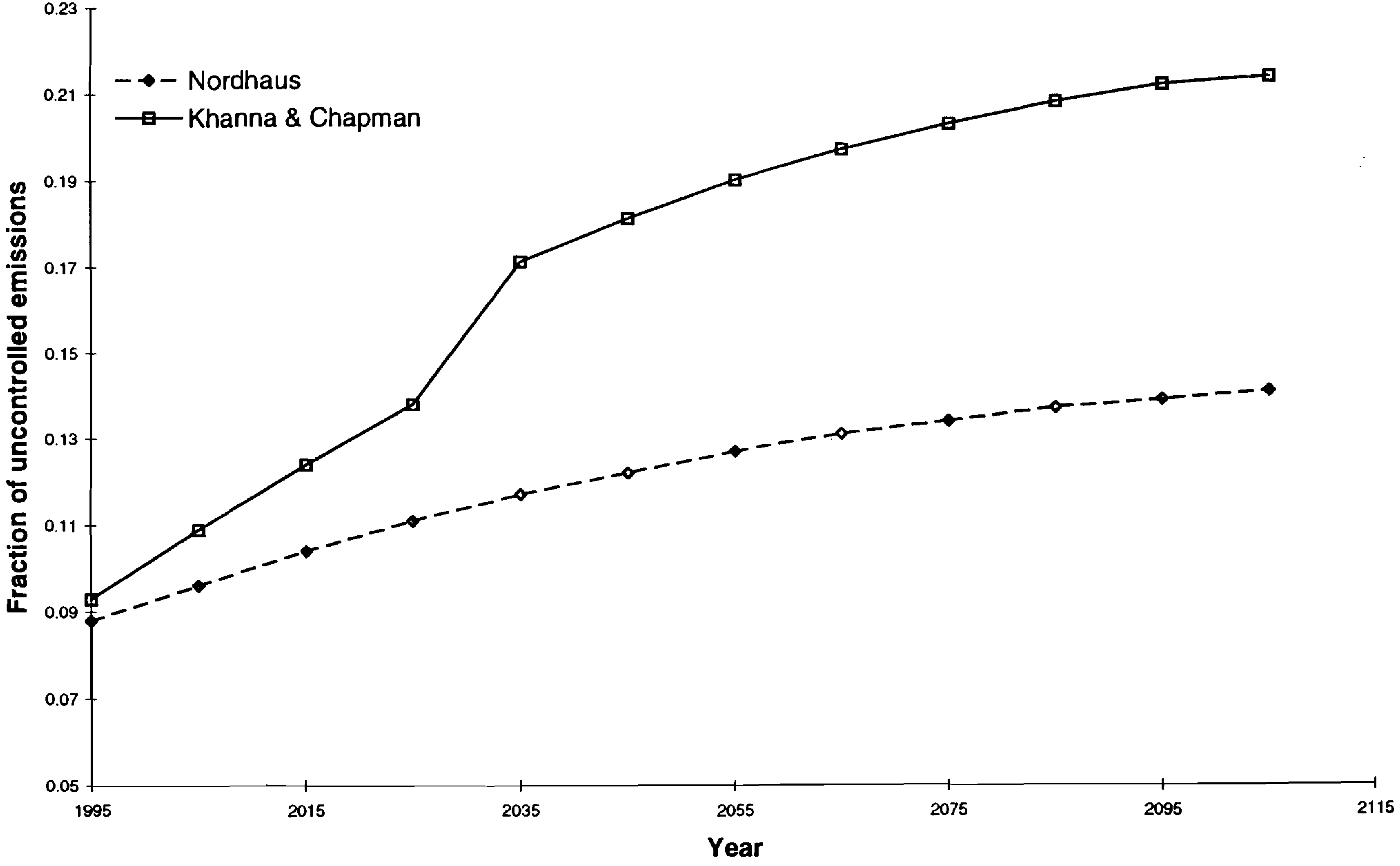
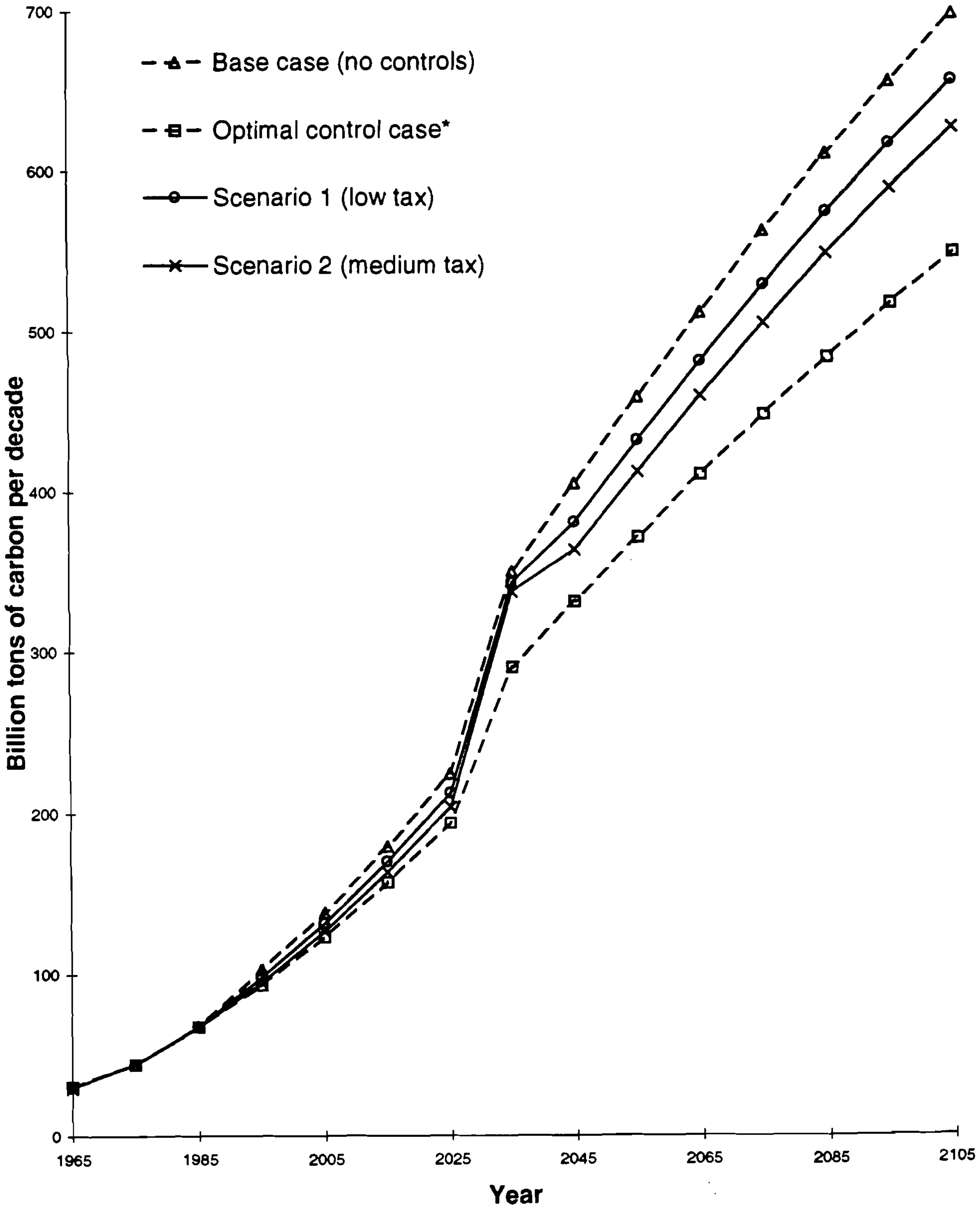


Fig. 9: CO2 Emissions Under Alternative Scenarios



* Same emissions trajectory as scenario 3 in table 4.

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